APL - North Pacific Acoustic Laboratory

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Grant Number: N00014-03-1-0181
http://www.apl.washington.edu/projects/npal/index.php
http://www.apl.washington.edu/projects/blue_water/index.html

DURIP Grant Number: N00014-07-1-0743
DURIP Grant Number: N00014-08-1-0797
DURIP Grant Number: N00014-08-1-0800

LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2008**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **APL - North Pacific Acoustic Laboratory**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,1013 NE 40th Street,Seattle,WA,98105**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of lowfrequency, long-range, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on longrange ocean acoustic signal transmissions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.

2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.

3. To develop theory and models to explain acoustic energy that propagates into the geometric shadow zone beneath deep caustics (shadow-zone arrivals) as measured with the NPAL network of bottom-mounted SOSUS receivers, the LOAPEX vertical line array, and ocean bottom seismometers.

4. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.

5. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.

6. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.

7. To design and conduct an experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. The NPAL network, operated and maintained by APL-UW, provides an actual laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The network consists of the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the locations of acoustic hydrophone arrays in the NPAL network.

The second avenue includes highly focused, comparatively short-term experiments.
The last NPAL experimental effort actually consisted of three coordinated experiments. APL-UW conducted the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), SIO was responsible for the SPICEX experiment, and MIT and OASIS performed the Basin Acoustic Seamount EXperiment (BASSEX). We are currently planning a major experimental effort in the Philippine Sea. Again the primary institutions will be APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT). The first effort in the Philippine Sea will be a Pilot Study / Engineering Test to be conducted in April-May of 2009. During this effort APL-UW will also provide support to researchers from the Marine Physical Laboratory (MPL) who are being supported

by the signal processing code of ONR. The main experimental effort in the Philippine Sea will begin in 2010.

As we prepare for the next major experiment, funding from the Defense University Research Instrumentation Program (DURIP) is providing significant support. In particular, this report includes activities funded by three DURIP grants (N00014-07-1-0743, -0797, and -0800).

The approach of NPAL also includes collaboration with a number of researchers from several other institutions who provide further analysis of NPAL experimental data and theoretical development. The collaboration is enhanced by holding yearly NPAL conferences usually near Seattle or San Diego.

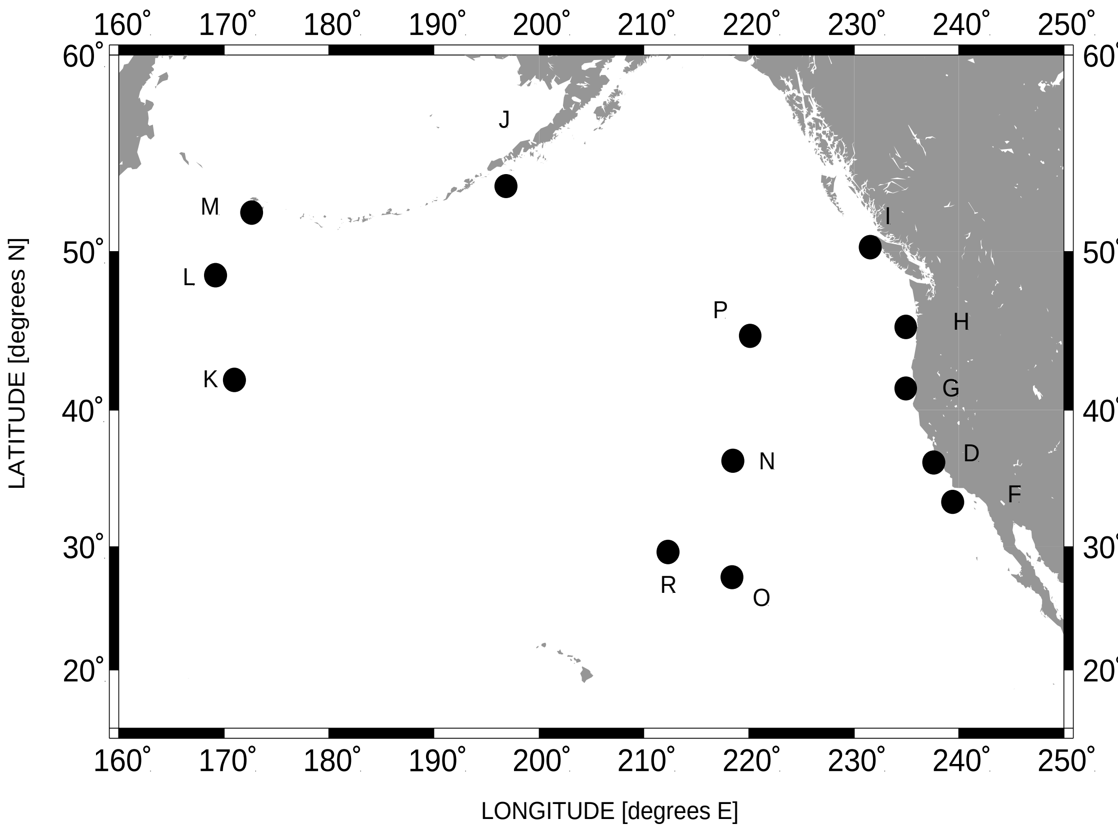

Figure 1. The NPAL hydrophone array network. The locations of arrays identified by the letters R, D, E, and F are exact. The other locations are notional. The entire network is controlled and monitored from APL-UW.

WORK COMPLETED

NPAL Acoustic Network. We completed and submited a paper on long-term low-frequency ambient noise trends to the *J. Acoust. Soc. Am.* Further calibration efforts (beyond those described last year) were required to correct for amplifier-to-amplifier variations for systems G and H. We now have results for systems F, G, and H (See Figure 1 for locations). Figure 2 is a composite figure showing trends originally reported by Ross [1] and recent trends as measured by APL.

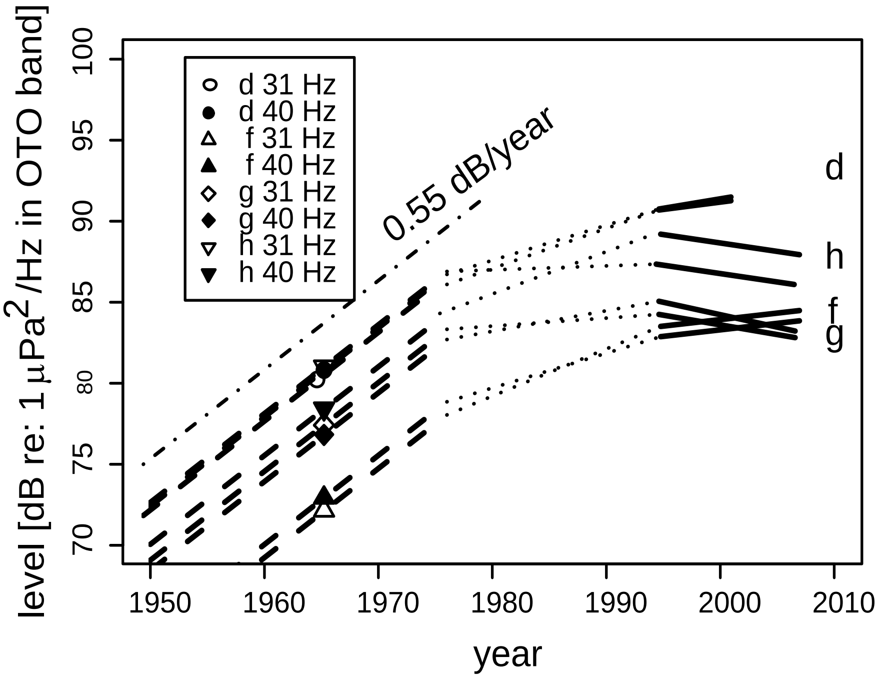

Figure 2. A comparison of APL measurements taken at 4 receiver sites (d, f, g and h) from 1994 to present (solid black lines)) with measurements acquired circa 1965 from the same sites, at 31 and 40 Hz (symbols). These frequencies are thought to be most representative of the contribution due to merchant shipping. The heavy dashed lines represent the general trend reported by Ross, based on measurements from the 1950's through the 1960's. Dotted lines connect trend lines for each site. The rate of increase has fallen off or reversed in the last quarter century. At sites d and f, the noise levels continue to increase, but not so at the two northern sites (g and h).

An unexpected result is the relative contribution of singing baleen whales. Figure 3 shows time series data from site F. At frequencies below 20 Hz the whalesong dominates periodically each year and also persists throughout the remainder of each year.

It is interesting to note that the whalesong component has virtually kept pace with the traffic noise. This can be seen by defining a crude measure of signal to noise ratio (SNR) where the "signal" is the baleen whalesong component in the one third octave band 12 (14 – 18 Hz) and the "noise" is the traffic component in one-third octave band 14 (22 – 28 Hz). The results for both the Wenz data [2] and the APL data are shown in Table 1. The data seem to suggest that the "SNR" has improved, i.e., the whalesong component has actually increased more over the past 40 years than the traffic noise component.

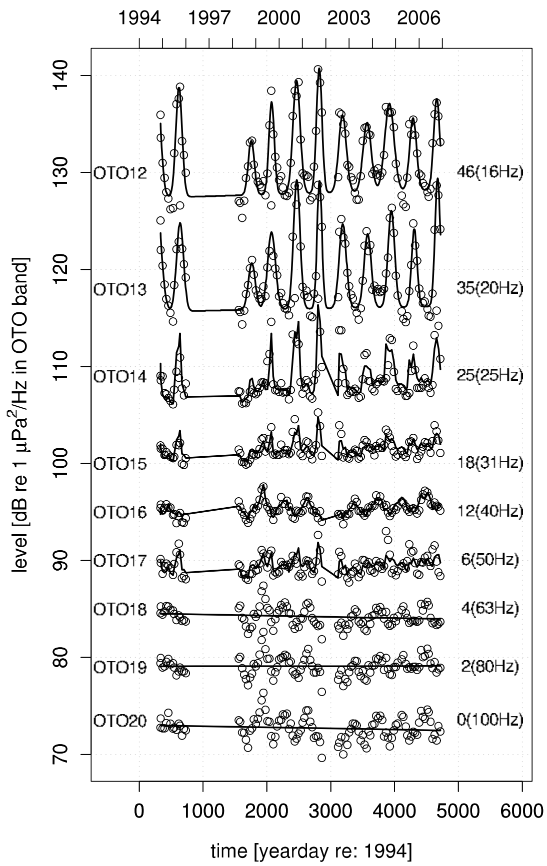

Figure 3. Time series data from site F for one-third octave bands 12 to 20 (circles, one value per month) and a model fit (black line). The dominant feature in bands 12 and 13 (center frequencies 16 and 20 Hz) are the annual contributions from baleen whales. Closer inspection (not shown) shows that the ambient sound does not seem to decrease to a "background" level between annual whalesong peaks, implying that, at these frequencies, the whalesong contribution is still at least as strong as any anthropogenic contribution throughout the year, which further suggests that the neighborhood of the site is never completely whale-free.

Table 1. Crude estimates of the whalesong SNR based upon Wenz's data (circa 1965) and the APL data (1994-2006). In both data sets it is assumed that only the whalesong signal occupies the one-third octave band 12 (14–18 Hz) and only the noise occupies the one-third octave band 14 (22–28 Hz). All values are in decibels.

Site	SNR (Wenz)	SNR (APL)	
D	-2.2	-1.5	+0.7
F	-3.2	+1.9	+5.1
G	-2.9	-2.2	+0.7
H	-1.8	-0.8	+1.0

The shore site for receiver R (Figure 1) is located on Oahu, HI. The site (Building 1767) was formerly within the Barbers Point Naval Air Station. This station is now part of a Base Realignment and

Closure process. We had obtained an easement for the undersea array cable as it comes on land to the building site and believed that this action would protect the shore building from being converted to another use; however, federal legislation conveyed the Navy lands along the northern edge the former base, including the receiver site, by the fall of 2008. To this end, the Navy signed a tentative agreement with Ford Island Properties (Hunt Construction) to convey the involved 499 acres including Building 1767. Initially, the property is to be leased to Hunt while they seek the necessary zoning entitlements from the State and City. Fortunately, many discussions with the Naval Facilities Engineering Command, HI, the US Navy Commander, Navy Region Hawaii, and the Office of Naval Research, resulted in an agreement with Ford Island Properties that will allow us to use the building without cost until February 2012. Hopefully by this time we will be able to arrange another structure for the cable termination on property that will be retained by the US Navy.

As a result of this base closure, land-line phone communication with our site equipment became impossible. To solve this problem a wireless broadband modem was installed and the communications are better now than ever.

Most of the acoustic receivers shown in Figure 1 were used to collect a time series of acoustic travel times from sound sources located near the Island of Kauai, HI and from the Pioneer Sea Mount near northern California. The measurements are accurate to about 10 ms. The Pioneer source transmitted for all of 1996 and into early 1997, but mitigation efforts related to marine mammal observations resulted in spotty transmission intervals until early 1999 when transmissions ceased. A second permit for this source was not pursued due to the perceived opposition. The Kauai source transmitted consistently through all of 1998 and most of 1999 when its permit expired. The environmental impact statement process was repeated and the Kauai source began transmitting again in 2002 and continued until 17 September 2006.

Because the acoustic travel times are sensitive to the ocean temperature through which they are traveling, these measurements provide a large-scale measure of the heat content variability over the decade-long time series. Dushaw et al. (see Publications) have submitted a paper that compares the measured acoustic travel times with travel times based upon in situ sound speed measurements and upon numerical ocean models; specifically, the Jet Propulsion Laboratory (JPL-ECCO) model and the Parallel Ocean Program model. The comparisons show that the measured acoustic data provide better resolution of large-scale variability of the ocean interior than either satellite or in situ measurements, and it is clear that the measured acoustic data can provide important constraints on the output of these models.

Because several acoustic multi-paths exist between each acoustic source and receiver, and because the travel times for these paths fluctuate over the seasons and a few paths may disappear and reappear, the tracking of the travel times for each path can be difficult. To ensure reliability in the time series data an independent tracking effort was made. Figure 4 provides the results of this effort. Although there are minor differences between the two data time series they do not alter the previous observations and the data also support the major conclusion that there has been no significant climatic heat content change in the NE Pacific Ocean during the decade from 1996 to 2006.

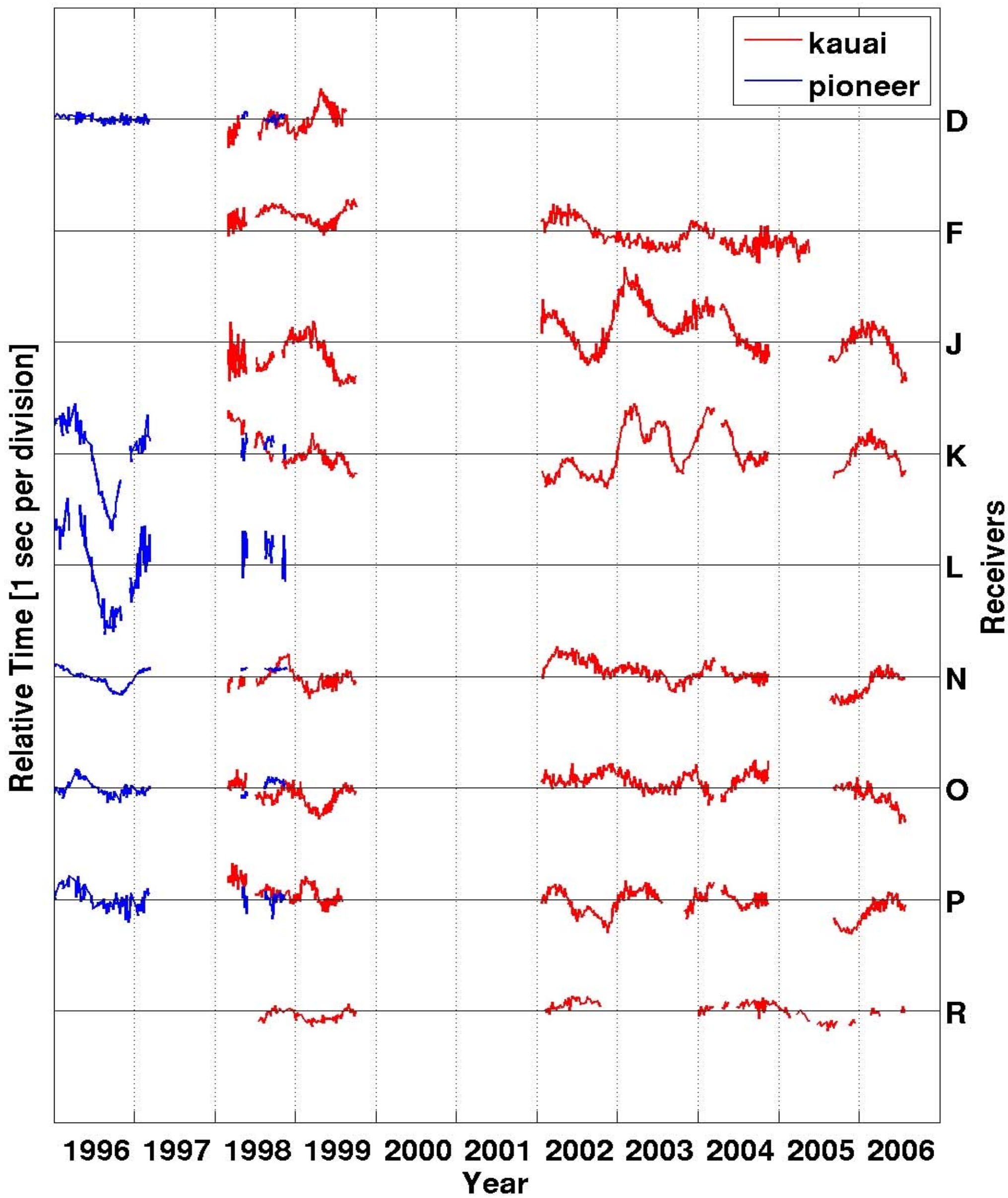

Figure 4. The variability of acoustic travel times from a projector on Pioneer Sea Mount (blue) and from near Kauai, HI (red) to receivers (capital letters) illustrated in Figure 1. Absolute travel times have been removed to show the variability and the vertical grid spacing represents 1 second of travel time variability.

In June of 2008 an attempt was made to recover the ATOC acoustic source that was left on the Pioneer Sea Mount. It was hoped that this source would provide a back up for our existing HX-554 low frequency projector. We left port in San Diego with an estimated on-site recovery window of 52 hours; although the recovery was expected to require only 16 hours. Due to problems with the port side engine on the R/V Atlantis, we arrived late with only 11 hours available to complete the recovery.

Furthermore, the seas had deteriorated to the point where a recovery would have been risky to equipment and personnel so the effort was aborted.

LOAPEX Analysis. As co-authors on a paper with Natalie Grigorieva (St Petersburg State Marine Technical University) we assisted in the submission of a paper to the *J. Acoust. Soc. Am*. We had previously supplied pulse-compressed intensity data for her analysis. Efforts in this period involved proof-reading, manuscript preparation, submittal of the paper, and correspondence with *JASA/AIP*.

APL-UW researchers also co-authored a paper with Ralph Stephen et al. (WHOI) and submitted it as a JASA Letter to the Editor. It is based on preliminary results from the LOAPEX ocean bottom seismometers (OBSs) with comparisons to the (deep) vertical line array (DVLA). During discussions amongst co-authors, issues were raised regarding the data processing and data interpretation. We undertook to process via several different algorithms all the LOAPEX DVLA lower subarray lowest hydrophone receptions from all stations for all transmissions at a source depth of 350m. Three different algorithms were used:

1) *A posteriori* Doppler correction on individual 20 minute transmissions, followed by coherent averaging within the 20 minutes, then pulse-compression, followed by incoherent averaging across transmissions. (The Doppler correction here merely compressed/expanded the signal until it matched a non-time-dilated waveform. No *a priori* knowledge of inter-platform velocities was used.)
2) The same, but without any Doppler correction..
3) Incoherent (i.e., magnitude) averaging of pulse-compressed sequences within each 20 minutes, followed by incoherent averaging across transmissions.

Typical results are shown in Figure 5. As expected, Doppler compensation provides the best peak-to-background "SNR", but this performance is only slightly better than non-Doppler processed coherent averages. The completely incoherent processing has the worst peak-to-background ratio, but essentially all the arrivals are still identifiable. This analysis indicates that Stephen's processing (algorithm 3) did not introduce extraneous features into the data interpretation.

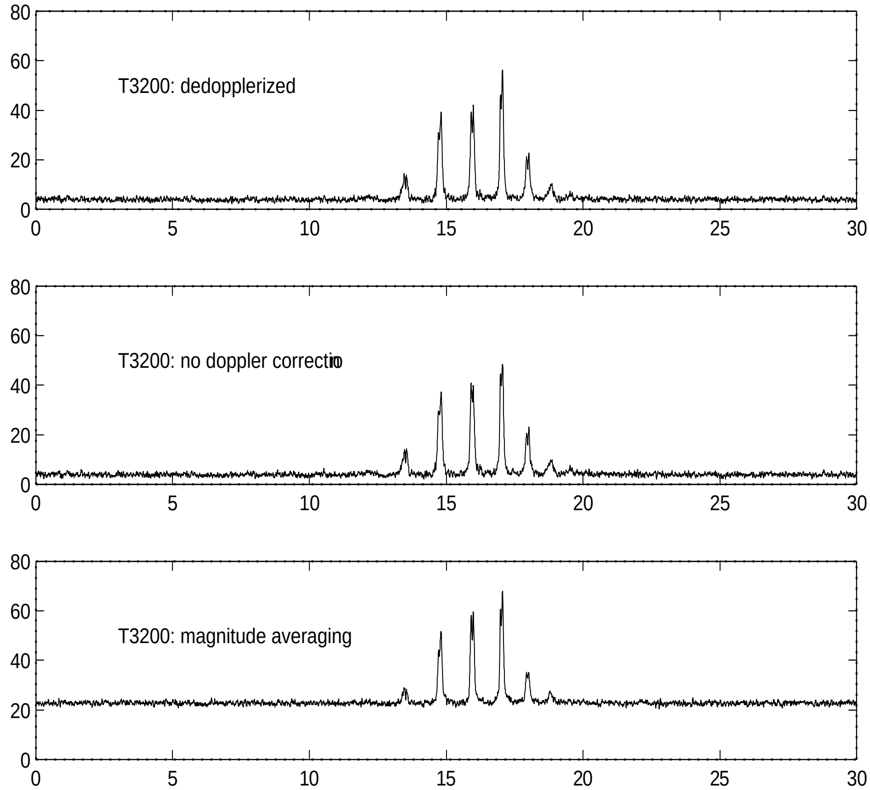

Figure 5. DVLA lower array, bottom hydrophone, processing comparison for transmissions from station T3200 (3200 km range.) Even completely incoherent averaging can extract identifiable arrivals from the background.

Philippine Sea Simulations and Planning. During this fiscal year there have been several meetings and phone conversations about the detailed plans for the Philippine Sea effort. Most of the planning has been focused on the 2009 Pilot Study / Engineering Test. As a result, a draft test plan [3] has been compiled. Although ship schedules were not finalized by the end of the fiscal year, it is expected that Worcester (SIO) will use the R/V Melville to deploy a source mooring and a new vertical line array in the late March to early April time frame, and upon her return to port, Mercer (APL-UW) will take the R/V Melville out to conduct suspended and towed acoustic source transmissions, and towed CTD Chain measurements. Simultaneous with Mercer, Baggeroer (MIT) will be aboard the R/V Kilo Moana towing the FORA horizontal hydrophone array.

The new SIO vertical line array utilizes self recording hydrophones and inductive coupling to the mooring wire for communications and control. It is hoped that in 2010 this array will consist of five sub-arrays, each having 30 hydrophones, and that it will cover most of the water column. In 2009 the array is expected to consist of two sub-arrays, a deep sub-array and an axial sub-array. The placement of hydrophones on the deep sub-array has been designed to measure the vertical dependence of ambient noise, and the axial sub-array placements were designed by Wage (George Mason University) to resolve the 10 lowest modes at 250 Hz. Figure 5 provides a ray trace simulation for the Philippine Sea with a source depth of 1000 m and the hydrophone depths indicated by horizontal lines. A corresponding time front plot for a range of 50 km is shown in Figure 6.

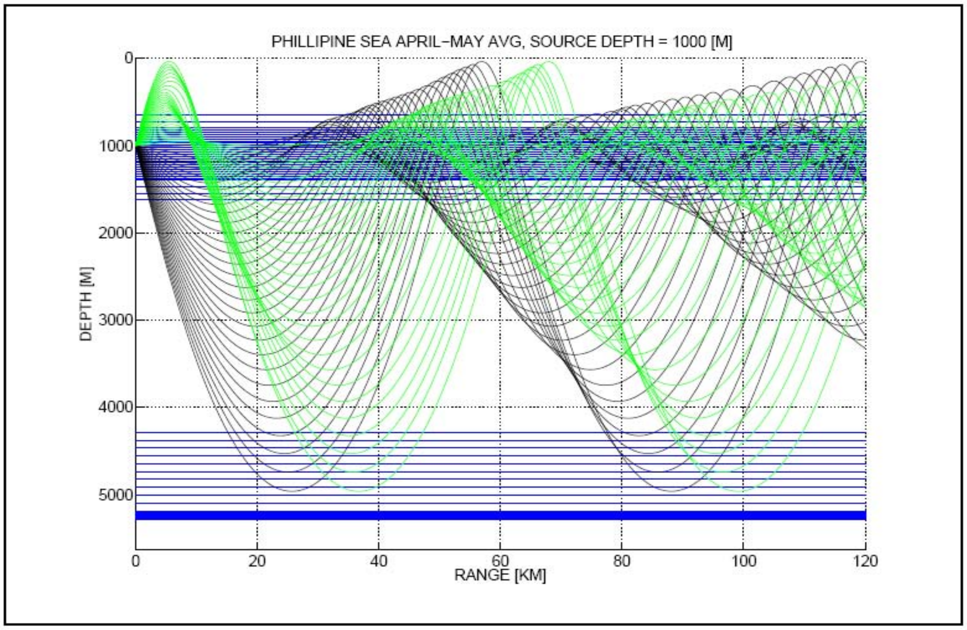

Figure 5. Rays leaving a source at angles of plus and minus 16 degrees from the horizontal. Only rays that do not encounter the surface or bottom are shown. Rays leaving the source with positive angles are shown in green and those with negative angles are shown in black. Blue lines represent planned hydrophone depths. The solid appearing blue band near the bottom is a result of the dense 5-meter spacing here.

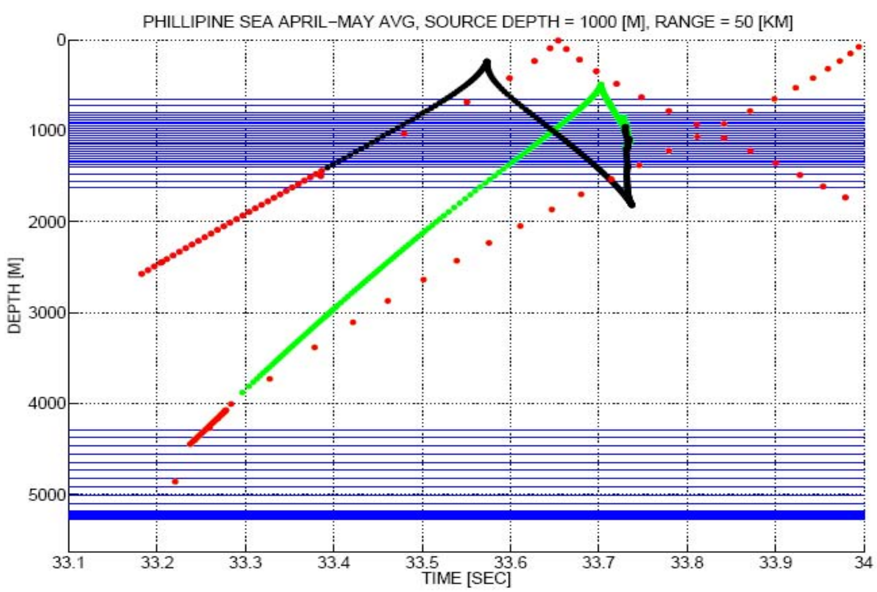

Figure 6. Timefront at 50 km with rays leaving the source at angles between +/- 20 degrees in 0.05 degree increments. Red dots correspond to rays that have reflected off the surface or the bottom, or will reflect before they reach a range of 100 km.

The planned geometry of the Philippine Sea Pilot Study / Engineering Test is illustrated in Figure 7.

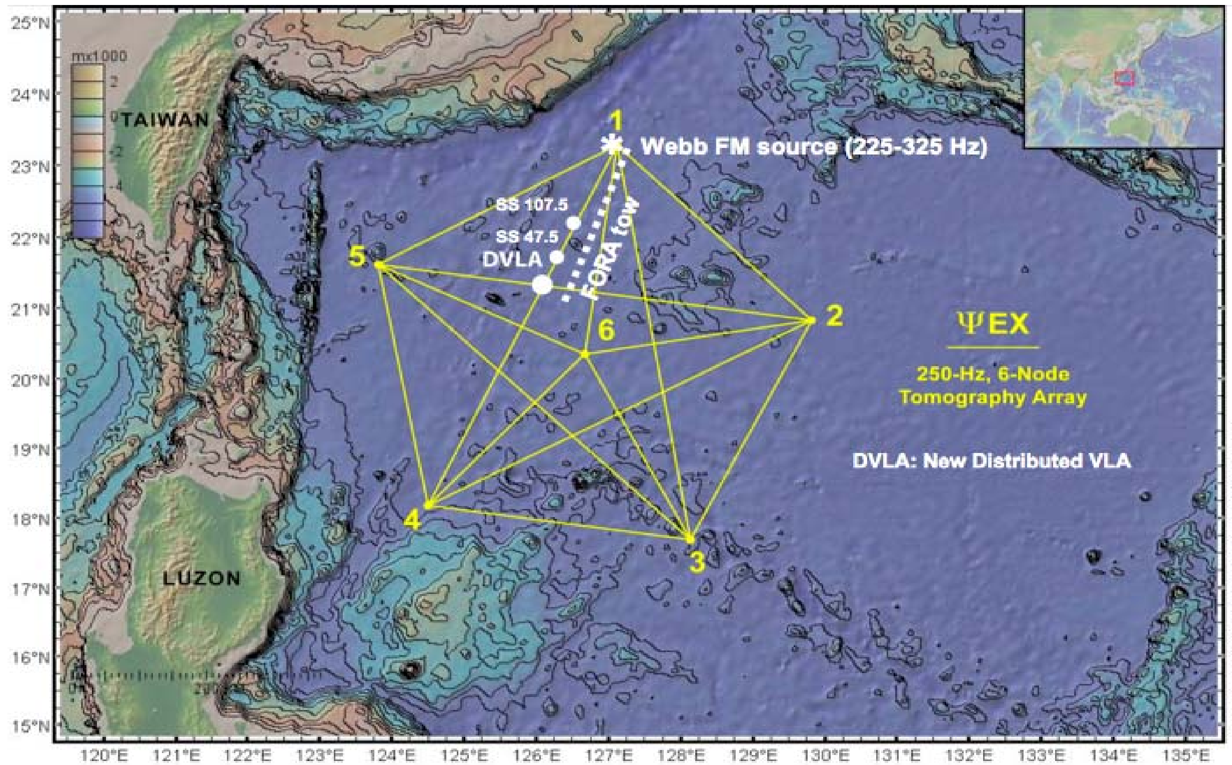

Figure 7. 2009 Philippine Sea Pilot Study/Engineering Test. A moored acoustic transceiver (1) will transmit to a Distributed Vertical Line Array (DVLA) located at the intersection of the 1-4 and 2-5 paths. Acoustic sources will be lowered from shipboard 47.5 km and 107.5 km from the DVLA and towed between the DVLA and 1.. The towed FORA array will record transmissions from both the moored and ship-suspended sources. Towed CTD Chain measurements will be made between the DVLA and 1.

A detailed transmission budget for the APL-UW source transmission was submitted to ONR and Marine Acoustics, Inc. to allow the preparation of an environmental assessment and any permits that may be required.

In support of operational planning for the Philippine Sea Pilot Study/ Engineering Test (PSIEX09), we performed several CAFI calculations [4] for rays launched from proposed ship stop "SS0.5" (50 km from the vertical line array receiver) and ship stop "SS1.5" (111 km from the VLA.) . CAFI produces numerous statistics: Figures 8 and 9 show predicted intensity correlation times, for signal frequencies of 75 Hz and 250 Hz, respectively. As expected, the 250 Hz signal has a shorter correlation timescale than the 75 Hz signal, and increasing range also causes additional de-coherence. An important result here is the predicted timescales themselves. Coherence times of hundreds of minutes will require hours of transmissions to observe. These kinds of predictions can shape the observational strategies for both the 2009 and 2010 at sea efforts.

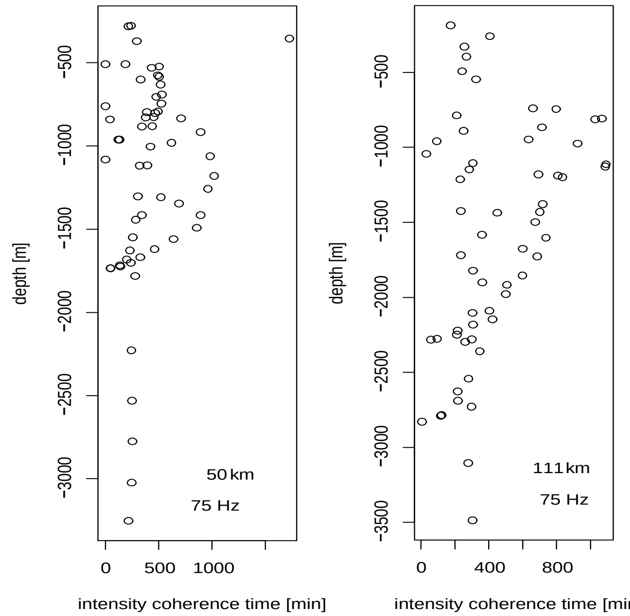

Figure 8.   CAFI predictions of intensity correlation time, 75 Hz, for ship stops SS0.5 and SS1.5 (47.5 km and 107.5 km, respectively.) Source depth 1000 m. Statistics plotted against the depth of the associated ray at the receiver range. Rays were launched from 15 to -15 degrees.

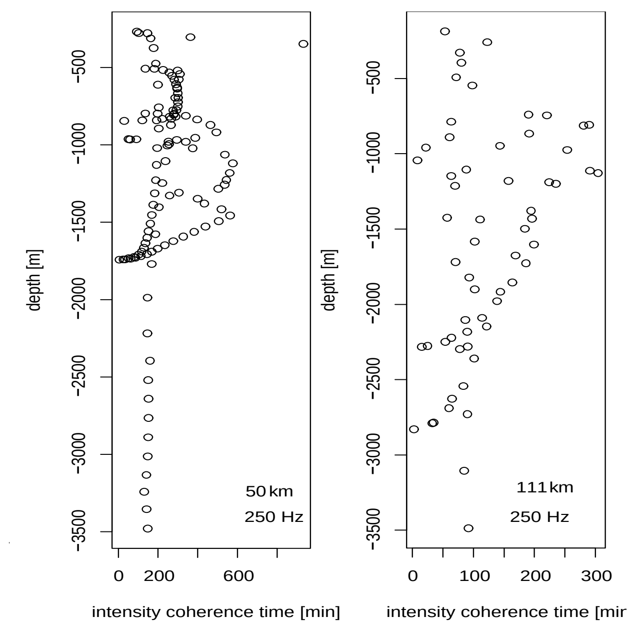

Figure 9. CAFI predictions of intensity correlation time, 250 Hz, for ship stops SS0.5 and SS1.5 (47.5 km and 107.5 km, respectively.) Source depth 1000 m. Statistics plotted against the depth of the associated ray at the receiver range. Rays were launched from 15 to -15 degrees.

Underwater Deployment Instrumentation – DURIP (N00014-07-1-0743). Although this DURIP grant was awarded for FY2007 it was extended so that the instrumentation acquired with this grant would interface more effectively with instrumentation obtained with a DURIP grant described below. For example the purchase order for the acoustic source electrical/mechanical deployment cable that was

originally planned to be purchased with this grant was modified to procure an electrical/optical/mechanical (EOM) cable that will support calibration, navigation, and monitoring hardware that was purchased with a DURIP grant described next.

The present DURIP was focused heavily upon equipment necessary to use the broad band acoustic source know as the Multi-Port transducer. This transducer system is targeted for the Philippine Sea experiments in 2009 and 2010, where it will provide wideband signals with a carrier frequency near 300Hz.

We subcontracted with Image Acoustics, Inc. (Cohasset MA) for the design of a tuner/transformer for the transducer. There are two requirements for the tuner: (1) step up the voltage delivered down the cable, thus decreasing the voltage requirements for the power amplifier (and cable); and (2) adjust the phase of the signal in order to minimize the reactive power exchanged with the transducer.

Once the design had been delivered, we subcontracted to Coiltron Inc (Tigard, OR) for the actual fabrication of the tuner. Coiltron had to obtain a custom core (and associated bobbin) to meet our requirements.

As noted by Birdsall and Metzger [5] in the ATOC project, tuner design and transducer performance are more subtle when considering wideband signals. Traditional narrowband considerations are not enough. Therefore, we also developed a simplified equivalent SPICE electrical model of the transducer/tuner combination that reproduced the system electrical and acoustical characteristics with fair fidelity. This allows us to predict the time-domain response for arbitrary input signals. Model characteristics were compared to corresponding empirical measurements made by APL-UW on Lake Washington in 2006. Although the double resonances of the device (see Figure 10) provide an overall low-Q broadband capability, the response of the system will introduce significant signal distortion. Signal equalization will therefore be required to "smooth out" the transfer function over the main band. A fair approximation was achieved by Image Acoustics, Inc. using a hardware equalizer in real-time.

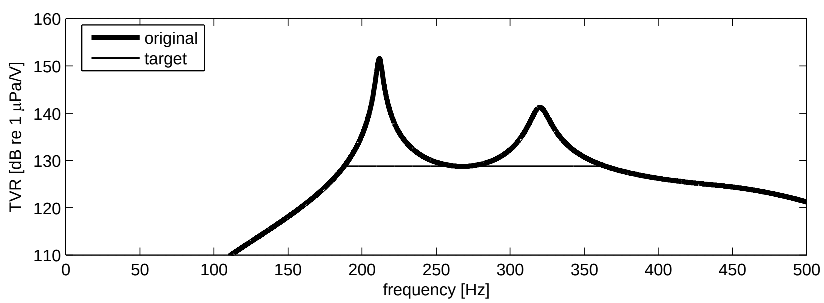

Figure 10. Modeled Multi-Port transmit voltage response (TVR) (heavy black lines). The thin line indicates the reduction goal and pass band after equalization.

We plan to test the Multi-Port system in Lake Seneca early in the next fiscal year.

Instrumentation for the Philippine Sea Experiment – DURIP (N00014-08-1-0797). This DURIP grant has provided a number of instruments to improve the reliability and safety of our field work. Signal durations in the Philippine Sea will be extremely long, on the order of 48 hours. The generation of long-duration, high-power acoustic signals required new instrumentation including a broad-band amplifier and low-level signal generation hardware and software. The detailed design of the

experiment (e.g., depths and ranges to the other assets) requires extensive computer simulations with a parabolic equation acoustic propagation code and a numerical model of the effective acoustic scattering. To accomplish these simulations a small computer cluster is required. The requirement to precisely navigate the location and velocity of the projectors will be met with an acoustic tracking system. The control and data logging features of this system will also provide for the recording of the projector internal temperature and pressure.

The computer cluster that was ordered consisted of a Rackform iServ R526, six Rackform iServ R254s, one HP switch port, one APC rack enclosure, one 17-inch Belkin rack console, and an APC smart UPS. The cluster arrived at the end of the fiscal year and will be operational early in the next fiscal year.

The NPAL community as a whole has expressed a sincere desire to have acoustic transmissions with very long durations, perhaps as long as 48 hours. Previous transmissions with our acoustic sources have been limited to a maximum duration of 120 minutes. The primary purpose is to explore the limits of the very long phase coherence that has been observed in previous experiments. To accomplish these long transmissions some new instrumentation components were required. The first is a new power amplifier. Our existing power amplifier was damaged in an electrical storm and was not capable anyway of providing power across the entire frequency band of the HX-554 and Multi-Port transducers that are planned for use in the Philippine Sea. An L50 power amplifier from Instruments Inc. was ordered. The L series amplifiers contain regulated power supplies, a Pre-Amplifier PWB, Output PWBs, and an output transformer system. The L series Output PWB is a current source. Voltage feedback is used to create a voltage source or resistive source. This amplifier is dual rated. That is, it is capable of both continuous as well as burst output. During continuous output into a reactive load, the heat sinks warm up. The heat sink temperature is sensed by the Pre-Amplifier and used to determine a safe current limit. While driving short tone bursts, or resistive loads, the heat sinks are cooler, therefore the current limit is increased by as much as 2.5 times. This function is automatic and on-going, cycle by cycle. This enables the amplifier to safely maximize output power under all conditions. Each bank of 10 Output PWBs in this amplifier is wired independently to its own output transformer. This enables the L50 to obtain superior high frequency performance. In addition, the output transformers have multiple secondary windings with taps to match various loads. These secondary windings are put in series and parallel combinations. This is done with relays which are always "cold switched" since the relays are commanded to move only after the amplifier has been automatically inhibited. The various load impedance taps may be selected by a front panel switch or controlled remotely. This feature will eliminate rewiring the transformers at sea when the projectors are interchanged. The amplifier is expected to be delivered in December 2008.

In general, the type of acoustic transmissions used in our work are either broad band phase-coded, maximal-length binary sequences, or source compensating frequency-multiplexed non-linear slides. These signals are generated from specialized hardware and software. Our existing signal generation equipment was based on a 15-year-old 80486 PC running DOS, an obsolete National Instruments data acquisition (DAQ) board, and a custom discrete logic timing board. The signal waveform output must be synched to a precision GPS clock, providing microsecond timing accuracy, via the timing board, the DAQ, and custom software. Components which have failed over the years have been replaced with parts salvaged from other systems. There were no more such spare salvaged components available. All components, with the exception of the timing board, were utterly obsolete, so there was no option to purchase replacement parts. Continuing dependence on this system would result in a total loss of

transmission data in the increasingly likely event that any aging part should fail. A replacement signal generation system was required.

We have upgraded our signal transmission capability by replacing our aging and obsolete 80486/DOS computers with 80686/Linux systems. A key component of this upgrade has been replacing the old National Instruments AT-MIO-64F5 data acquisition cards with National Instruments PCI-6071E cards (purchased with an earlier DURIP grant) and finding/installing/integrating corresponding device drivers. We selected the open-source drivers from COMEDI over the new National NIDAQmx Linux drivers because (a) the National driver was essentially ported from the COMEDI community, and (b) the COMEDI driver is delivered as source code, whereas the source for the National driver is proprietary and not available. Source code availability was critical during development, as it enabled us to match our requirements through to the hardware capabilities by rendering transparent the operations from user space to kernel space to hardware features documented in the NI manuals.

Design goals for the new system are:

1) Input signals defined in open-standard WAV file format. You can play these signals on your laptop if you like.

2) Support for very long signals. The previous transmission program was limited to signals defined with about 65K samples – about 30 seconds for ATOC-like frequencies. The new system handles signals containing up to 4 gigasamples (this limitation is due to the size of the signal size variable defined in the WAV format.). This feature enables use of multi-symbol acoustic modem signals, for example.

3) An optional 300 second "ramp";

4) GPS-synchronized timing (based on Network Time Protocol (www.ntp.org) and a custom APL shared-memory driver.

5) Signal launch precise to a few microseconds with respect to a GPS-based clock.

6) Simultaneous transmit (one channel) and receive (6 channels) at the same sample rate. This feature is a carry-over from the previous version, and permits the user to capture not only the drive signal, but voltage and current monitors from the power amplifier output, the two main clocks, and one raw acoustic channel, usually used for the hydrophone monitor. These receive channels provide key diagnostic and verification information on system performance.

7) Continuous transmission for 48 hours (or so) without dropping samples for signals at sample rates up to 10 kHz. Duration is limited by the number of diagnostic channels captured and therefore the hard drive size (!).

Support for long duration signals required a redesign (from the original Metzger implementation) of the buffering strategy. A functional block diagram of the buffer structure for streaming analog output is shown in Figure 11.

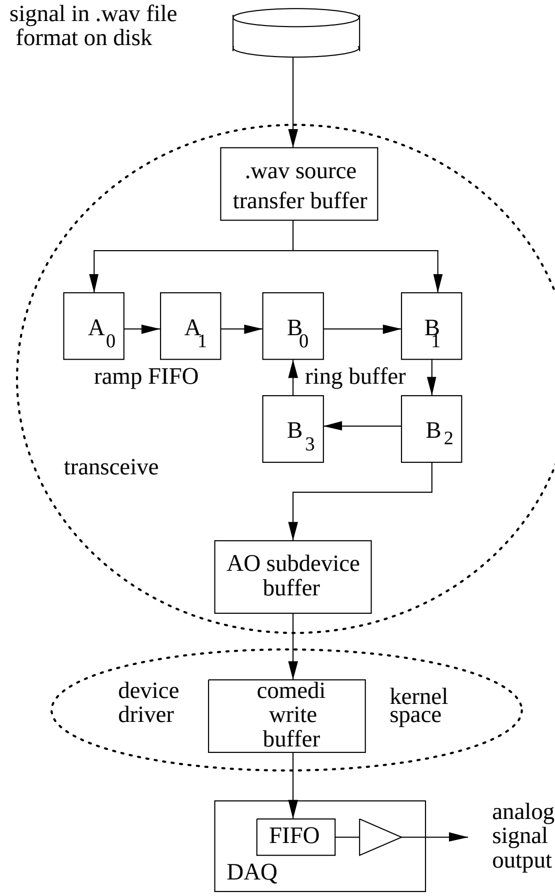

Figure 11. Buffer structure in the transmitter program. The quad ring buffer (B0, B1, B2 and B3) supports continuous streaming output for signals of any length. An optional ramp (here, A0 and A1) can be added to the ring buffer to comply with marine mammal mitigation. The COMEDI write buffer is sized to absorb latencies of more than 1 second while sampling at 10,000 samples per second.

The primary concern with the Linux operating system (or any Unix-based operating system, or even Microsoft Windows) is the inherent latency of a multitasking operating system, a concern not relevant for the original DOS-based systems. This concern is addressed in the driver design by incorporating user-defined, read and write FIFO buffers. We oversize the buffers, so that they are large enough to hold more than one second's worth of data at the highest sample rate. Testing to date has indicated no transmitter dropouts after more than one hundred cumulative hours of operation at either ATOC-like sample rates (2400 Hz) or the higher Multi-Port sample rate (9600 Hz).

The goals of our experimental methods are to combine high resolution environmental data with precisely controlled geometries for acoustic transmissions. The accurate navigation of our deployed projectors is a critical element in computing coherence functions for our received signals. We need to be able to separate signal de-coherence caused by source-motion Doppler, from that due to the ocean variability related Doppler. The best and most straightforward method of navigation down to 1000 m depths is an acoustic tracking system. With the DURIP described above we purchased several acoustic transponders that can be deployed on the bottom about our source positions, but they require a projector-mounted tracking system that interrogates the bottom-mounted transponders and receives

their replies. This tracking system must be located in the immediate vicinity of the acoustic projector. The heart of the system will be a Teledyne Benthos ATM-885 modem board that comes with a suitable tracking transducer, and a Persistor CF2 controller and data logger. This tracking system will interrogate up to four bottom-mounted transponders and detect and record their round-trip travel times back to its transducer. The battery powered tracking system will also record these travel times and send them to the surface via an optic fiber in the main electro-mechanical acoustic projector signal cable using TC Communications TC1705 RS232 optical converters.   As an inexpensive method of obtaining the transducer depth, we have incorporated a pressure sensor on the tracking system pressure case. We purchased a Paroscientific pressure transducer that will need to be integrated into the system. This data will also be recorded in the tracking system data logger and sent to the surface via the fiber link. There is some concern about the internal temperature of the acoustic sources. Because of the planned very long transmission durations it will be prudent to have a method of monitoring the internal temperature of the sources. To this end, a small temperature probe will be mounted inside the transducer transformers and the resulting signal will be sent to the tracking system pressure case where it will be recorded and sent to the surface via the fiber link. All tracking and sensor data will be recorded in the tracking system pressure case so that breakage of the optic fiber would not be catastrophic.

Expansion Towed CTD Chain – DURIP (N00014-08-1-0800). A major focus of the Philippine Sea experiment will be a study of the physics related to the performance of acoustic propagation models and the models that ultimately describe the ocean sound speed and its variability. The Philippine Sea is a highly energetic region and a detailed knowledge of this environment is required to develop and test both environmental and acoustic propagation models. Variability in the sound-speed structure due to internal waves, neutrally buoyant sound-speed perturbations, internal tides, and mesoscale eddies and fronts will unquestionably produce large fluctuations in the received signals reducing the temporal and spatial coherence. Although we plan to sample the water with conventional in-situ instrumentation such as conventional CTDs and XBTs, the best and a more synoptic measurement can be obtained by deploying a Towed CTD Chain directly along our propagation path. The goal is to eliminate uncertainty about the sound-speed description when comparing acoustic data and model outputs. To this end we have order a Towed CTD Chain System from ADM-Electronik (Germany). The main elements of the system are illustrated in Figure 12.

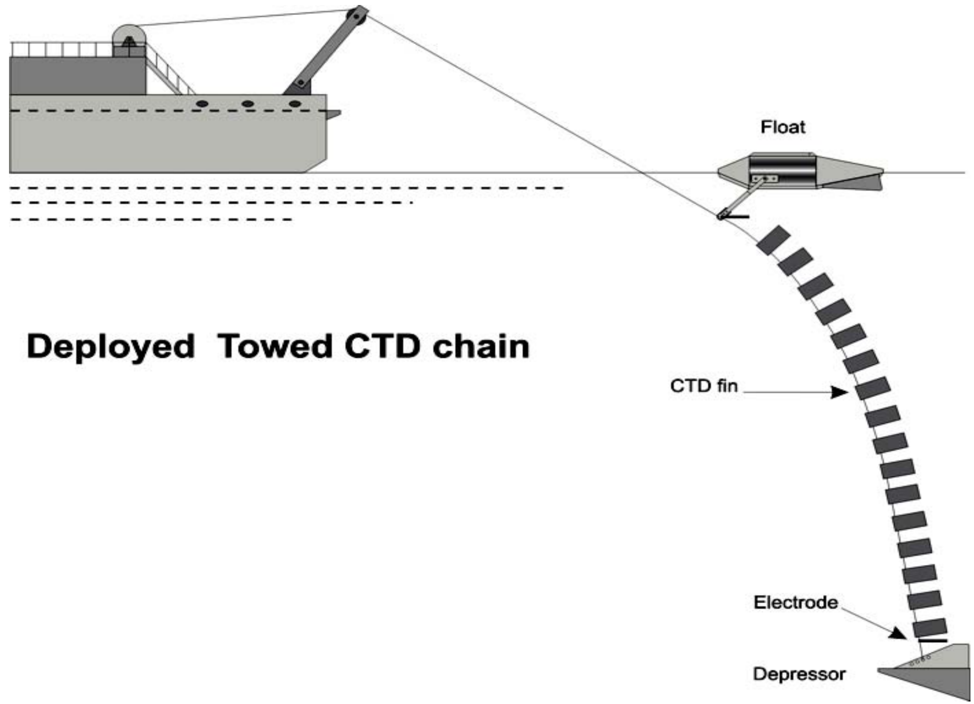

Figure 12. Main components of the Towed CTD Chain.

Our order included 50 CTD sensors and we will obtain, on loan, another 50 sensors from ONR via the Pennsylvania State University. The Towed CTD Chain will allow a two-dimensional description of the ocean to 500 m depth that cannot be obtained by other methods. Average resolution in depth will be 5 m, and a typical resolution in the horizontal will also be 5 m. The data will support the development and validation of upper ocean models that is currently lacking and a definitive comparison of acoustic data and prediction models.

The DURIP grant was expanded to account for the changing value of the US Dollar relative to the Euro, and to allow the training and acceptance testing to coincide with the Philippine Sea Pilot Study / Engineering Test. The system is scheduled for delivery in Seattle, WA on 11 November 2008.

RESULTS

Ambient sound measurements from receiver F (Figure 1) have shown that at frequencies below 20 Hz the singing of baleen whales dominates the ambient noise at seasonal peaks and persists throughout the remainder of each year. It was also discovered that the baleen whalesong appears to have kept pace with the annual increases in ambient noise levels and may in fact have increased faster than the backround noise level over the past 40 years.

Fortunately, many discussions with the Naval Facilities Engineering Command, HI, the US Navy Commander, Navy Region Hawaii, and the Office of Naval Research, resulted in an agreement with Ford Island Properties that will allow us to continue using the building that houses the shore-based electronics for receiver R (Figure 1) without cost until February 2012. Hopefully by this time we will be able to arrange another structure for the cable termination on property that will be retained by the US Navy.

Transmissions from the Pioneer Sea Mount acoustic source were terminated in 1999 and transmissions from the Kaui acoustic source were terminated in 2006. Receptions of these transmissions on the receivers shown in Figure 1 have produced a valuable time series since the travel times are nearly proportional to the heat content of the ocean through which the sound passed. Because the sources and receivers were fixed, and because the transmissions and receptions were accurately controlled by GPS-based clocks, the time series measurements are accurate to 10 ms. One evidence of this is the ability to "see" the diurnal tide signal in the travel time data. The time series indicates that there has been no discernable climatic trend to the heat content in the NE Pacific Ocean. In addition, comparisons with in situ data and high resolution numerical ocean models show that the measured acoustic data provide better resolution of large-scale variability of the ocean interior than either satellite or in situ measurements and it is clear that the measured acoustic data provide important constraints on the output of these models.

Ocean Bottom Seismometer (OBS) data taken during LOAPEX has produced remarkable results. Even though the OBSs were well below the reciprocal depth, receptions were recorded at a source range of 3200 km. As expected, Doppler compensation provides the best peak-to-background "SNR", but this performance is only slightly better than non-Doppler processed coherent averages. The completely incoherent processing has the worst peak-to-background ratio, but essentially all the arrivals are still identifiable.

Detailed plans for the Philippine Sea Pilot Study/Engineering Test have been completed and the APL-UW transmission budget has been submitted to ONR and Marine Acoustics, Inc. for the completion of an environmental assessment.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

RELATED PROJECTS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), N. Grigorieva (St. Petersburg State Marine Technical University), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), M. Wolfson (APL-UW), G. Zaslavsky (NY Univ.), and others. In addition, we have begun close collaboration with Gerald D'Spain who is funded by the signal processing code of ONR.

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